RESONANT OPTICAL POWER CONTROL DEVICES AND METHODS OF FABRICATION THEREOF

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FIELD OF THE INVENTION

The field of the present invention relates to optical power control devices. In particular, resonant optical power control devices, and methods of fabrication thereof, are described herein for modulating optical power transmitted through an optical fiber.

BACKGROUND

This application is related to subject matter disclosed in: U.S. provisional application Serial No. 60/111,484 entitled "An all-fiber-optic modulator" filed 12/07/1998 in the names of Kerry J. Vahala and Amnon Yariv, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein; U.S. application Serial No. 09/454,719 entitled "Resonant optical wave power control devices and methods" filed 12/07/1999 in the names of Kerry J. Vahala and Amnon Yariv, said application being hereby incorporated by reference in its entirety as if fully set forth herein; U.S. provisional application Serial No. 60/108,358 entitled "Dual tapered fiber-microsphere coupler" filed 11/13/1998 in the names of Kerry J. Vahala and Ming Cai, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein; and U.S. application Serial No. 09/440,311 entitled "Resonator fiber bi-directional coupler" filed 11/12/1999 in the names of Kerry J. Vahala, Ming Cai, and Guido Hunziker, said application being hereby incorporated by reference in its entirety as if fully set forth herein.

Optical fiber and propagation of high-speed optical pulses therethrough has become the technology of choice for high speed telecommunications. Wavelength division multiplexing (WDM) techniques are now commonly used to independently transmit a plurality of signals over a single optical fiber, each independent data stream being carried by a slightly different optical carrier wavelength. Signal carried by individual channels must be independently accessible for routing from a particular source to a particular destination. This has previously required complex and difficult-to-manufacture switching devices requiring extensive active alignment procedures

during fabrication/assembly, and as a result are quite expensive. Such devices may require conversion of the optical signals to electronic signals and back again, which is quite power consuming and inefficient. In the four patent applications cited above and incorporated by reference herein, a new approach is disclosed for controlling optical power transmitted through an optical fiber that relies on the use of resonant whispering-gallery-mode optical resonators for direct optical coupling to an optical fiber and enabling wavelength-specific modulation of optical signals. A thorough discussion of the features and advantages of such optical power control devices and techniques may be found in these four applications, already incorporated by reference herein.

The subject matter disclosed and/or claimed herein pertains primarily to the specific embodiments of such resonant WGM resonators, optical power control devices incorporating such resonators, and methods of fabrication and/or assembly thereof. It is desirable to provide such optical power control devices that may be readily and reliably manufactured and which will perform reliably and stably.

SUMMARY

Certain aspects of the present invention may overcome one or more aforementioned drawbacks of the previous art and/or advance the state-of-the-art of optical power control devices and fabrication thereof, and in addition may meet one or more of the following objects:

To provide a resonant optical power control device that may be reliably and reproducibly fabricated;

To provide a resonant optical power control device that may be reliably and reproducibly fabricated without resorting to active alignment procedures;

To provide a resonant optical power control device with low insertion loss;

To provide a resonant optical power control device with a free spectral range suitable for use in WDM applications;

To provide a resonant optical power control device wherein an optical wave propagating through an optical fiber is coupled to a resonant whispering-gallery-mode resonator;

To provide a method for fabricating a whispering-gallery-mode optical resonator on the circumference of an optical fiber;

To provide a method for fabricating a whispering-gallery-mode optical resonator on the circumference of an optical fiber by altering a physical property (diameter, refractive index, chemical composition, density, and so on) of a transverse resonator segment of the optical fiber;

To provide a method for fabricating an optical power control device wherein the optical fiber and the whispering-gallery-mode resonator are positioned and secured within alignment grooves on an alignment substrate;

To provide a method for fabricating an optical power control device wherein the whispering-gallery-mode resonator is provided with an alignment groove and/or flange for passive alignment within an alignment grooves on an alignment substrate;

To provide a method for fabricating an optical power control device wherein the optical fiber has a fiber taper segment for optically coupling to the whispering-gallery-mode resonator;

To provide a method for fabricating an optical power control device wherein the optical fiber may be heated and pulled to form a fiber taper segment within an alignment groove on an alignment substrate; and

To provide a method for fabricating an optical power control device providing a modulator for controlling optical properties of the whispering-gallery-mode resonator.

One or more of the foregoing objects may be achieved in the present invention by a method for fabricating a whispering-gallery-mode (WGM) optical resonator on an optical fiber, comprising the step of generating a differential of a physical property (diameter, density, refractive index, chemical composition, and so forth) of a transverse resonator fiber segment relative to the longitudinally adjacent fiber segments. The resonator fiber segment may therefore substantially confine a WGM optical propagating around the resonator fiber segment circumference at least partially within the resonator fiber segment. Specialized techniques for spatially selectively generating the differential may include masking/etching, masking/deposition, laser machining, laser patterning, combinations thereof, and/or functional equivalents thereof. The WGM resonator may be further provided with an alignment flange and/or groove for enabling passive positioning of the WGM resonator within an alignment groove of an alignment substrate. A preferred method for fabricating an optical power control device according to the present invention comprises the steps of: 1) fabricating a WGM resonator as described herein; 2) heating and pulling a transmission optical fiber to form a fiber taper segment; 3) fabricating an alignment substrate having a resonator-alignment groove and a fiber alignment groove thereon; 4) positioning and securing the fiber taper segment within the fiber-alignment groove; 5) positioning and securing the WGM resonator within the resonator-alignment groove so that the WGM resonator and the fiber taper segment are optically coupled (through close proximity and/or direct contact between them). The alignment grooves are fabricated at the correct depths and positions and with corresponding alignment grooves and/or flanges to enable the optical coupling without extensive active alignment procedures. A modulator may be provided as an integral component of the WGM resonator, provided directly on the WGM resonator, or as a separate assembly

positioned on and secured with respect to the alignment substrate. The modulator enables control of the optical properties of the WGM resonator, which in turn enables control of the optical power transmitted through the fiber taper segment of the transmission optical fiber.

Additional objects and advantages of the present invention may become apparent upon referring to the preferred and alternative embodiments of the present invention as illustrated in the drawings and described in the following written description and/or claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A and 1B show side and transverse cross-sectional views, respectively, of a WGM resonator fabricated on an optical fiber according to the present invention.

Figures 2A, 2B, and 2C show schematically intensity profiles for the three lowest order transverse whispering-gallery modes of a WGM resonator on an optical fiber according to the present invention.

Figure 3 illustrates a method for fabricating a WGM resonator on an optical fiber according to the present invention. All views are side views, and stippled shading indicates the presence of an outer coating on the outer surface of the optical fiber.

Figure 4 shows schematically an apparatus for highly concentric rotation of an optical fiber during laser machining or other fabrication process according to the present invention.

Figure 5 shows an optical fiber being laser-machined according to the present invention.

Figure 6 shows reduction of the diameter of a WGM resonator on an optical fiber according to the present invention.

Figure 7 illustrates a method for fabricating a WGM resonator on an optical fiber according to the present invention. All views are side cross-sectional views.

Figure 8A illustrates a method for fabricating a WGM resonator on an optical fiber according to the present invention. All views are side cross-sectional views, and the density of the stippled shading indicates the relative refractive index, density, and/or dopant concentration.

Figures 8B and 8C show reduction of the diameter of a WGM resonator on an optical fiber according to the present invention.

Figures 9A and 9B show a WGM resonator on an optical fiber with alignment and/or indexing structures provided thereon according to the present invention.

Figure 10 shows a transverse cross-sectional view of a resonator fiber segment having a modulator material provided on a portion of the outer circumference thereof according to the present invention.

Figure 11 shows a WGM resonator on an optical fiber having one truncated adjacent fiber segment and a modulator material provided on a portion of the fiber end-face thereof according to the present invention.

Figure 12 illustrates a method for assembling an optical power control device on an alignment substrate according to the present invention.

Figures 13, 14, and 15 are cross-sectional views (looking along a resonator-alignment groove) of optical power control devices according to the present invention.

Figure 16 is a top view of a WGM resonator on an optical fiber having alignment structures thereon that are engaged with corresponding alignment structures in resonator-alignment groove according to the present invention.

Figures 17 and 18 are cross-sectional views (looking along a fiber-alignment groove) of an optical power control device according to the present invention.

Figure 19 illustrates a method for assembling an optical power control device on an alignment substrate according to the present invention.

Figure 20 illustrates a method for fabricating a WGM resonator on an optical fiber with a modulator material provided on an end-face thereof according to the present invention.

Figure 21 is a side cross-sectional view of a WGM resonator on an optical fiber with a modulator material provided on an end-face thereof according to the present invention.

Figures 22, 23, and 24 are cross-sectional views (looking along a resonator-alignment groove) of optical power control devices according to the present invention.

Figure 25 is a top view of an optical power control device according to the present invention.

Figure 26 is a cross-sectional view (looking along a fiber-alignment groove) of an optical power control device according to the present invention.

It should be noted that the relative proportions of various structures shown in the Figures may be distorted to more clearly illustrate the present invention. In particular, the size differential and resonator thickness are greatly exaggerated relative to the underlying optical fiber diameter in the Figures for clarity. Various metal, semiconductor, and other thin films are also shown having exaggerated thickness for clarity. The text and incorporated references should be relied on for the appropriate dimensions of structures shown herein.

DETAILED DESCRIPTION OF PREFERRED AND ALTERNATIVE EMBODIMENTS

Preferred and alternative methods for fabricating a whispering-gallery-mode (hereinafter, WGM) optical resonator are illustrated in Figures 1 through 24. An optical fiber serves as the starting material for fabricating a ring-type WGM resonator. Use of a ring or disk WGM resonator substantially eliminates the problem of closely-spaced modes that typically characterize nearly spherical WGM resonators. Use of an optical fiber as the starting material insures that the resulting WGM resonator will be substantially circular, and facilitates subsequent optical coupling to and/or phase matching with an optical fiber, and assembly/alignment of the WGM resonator as part of an optical power control device. The WGM resonator is fabricated by generating a differential of some physical property of the optical fiber between a transverse resonator segment of the optical fiber and the two longitudinally adjacent segments of the optical fiber. The physical property differential enables substantial confinement by the resonator fiber segment of a substantially resonant WGM optical wave that propagates around the circumference of the fiber at least partially within the resonator fiber segment. A portion of the WGM optical wave comprises an evanescent wave extending outside the resonator fiber segment longitudinally and/or radially. The evanescent wave portion of the WGM optical wave enables optical coupling of the WGM optical resonator to other optical components and modification and/or control of the optical properties, behavior, and performance of the WGM optical resonator.

In a preferred method for fabricating the WGM resonator, the diameter is the property of the optical fiber for which a differential is generated (Figure 1). Optical fibers are commonly available commercially having a diameter of about 125 μm (higher refractive index core plus lower refractive index cladding, excluding any additional jacket material) and the finished WGM resonator may have a diameter ranging between about 10 μm and about 250 μm. A size differential of between about 0.1 μm and about 10 μm (with the resonator fiber segment 100 being larger than the adjacent fiber segments 200) is generally sufficient to substantially confine a WGM optical wave at least partially within the resonator fiber segment 100. The thickness of the resonator fiber segment 100 may range between about 0.5 μm and about 100 μm, preferably between about 1 μm and about 10 μm, and may most preferably be less than about 5 μm so that the WGM optical wave may extend longitudinally beyond the resonator fiber segment, and to reduce or substantially eliminate other WGM spatial modes having resonant frequencies nearby.

In particular, it has been observed that a WGM resonator having a diameter of about 125 μm, a size differential of 1-2 μm, and a resonator fiber segment thickness of about 5 μm may support a lowest-spatial-order WGM mode, but also higher-spatial-order WGM modes having planar nodal surfaces perpendicular to the axis of the resonator fiber segment (Figures 2A, 2B, and 2C). These higher-spatial-order modes are frequency shifted with respect to the lowest-order mode, thereby degrading the frequency selectivity (i.e., decreased free spectral range) of the WGM resonator. This problem may be mitigated in several ways. In a first method, it has been observed that a smaller size differential between the resonator fiber segment 100 and the adjacent fiber segments 200 (less than about 0.5 μm, preferably about 0.1 μm) confines the whispering-gallery-modes more weakly than a larger size differential, resulting in a lower Q-factor for the modes. This effect becomes substantially more pronounced for higher-spatial-order modes, which extend further beyond the resonator fiber segment than lower-order modes as shown in Figures 2A through 2C. Sufficient reduction of the size differential results in substantial suppression of all higher-order modes and the desired free spectral range for the WGM resonator. Alternatively, in a second method the thickness of the resonator fiber segment may be reduced from about 5 μm to about 1 μm. Higher-spatial-order whispering-gallery modes that extend longitudinally further beyond the resonator fiber segment will typically have a lower Q-factor than lower-spatial-order modes. Sufficient reduction of the resonator fiber segment thickness may substantially suppress all but the lowest-order mode and yield the desired free spectral range for the WGM resonator. The first of these methods may be more readily and/or economically implemented and lead to reduced manufacturing time and costs. Alternatively, a larger resonator thickness (perhaps several 10's of microns) may be desirable for enabling optical coupling of multiple fibers to a single WGM resonator; or a plurality of resonators positioned on the same fiber sufficiently close together to enable optical coupling between them may be employed to provide a tailored frequency filter function for optically coupling multiple fibers.

A preferred method for reducing the size of the adjacent fiber segments relative to the resonator fiber segment comprises the steps of: 1) providing the resonator fiber segment with a mask; 2) spatially-selectively etching the adjacent fiber segments, thereby reducing their diameters relative to the diameter of the resonator fiber segment; and 3) removing the mask (Figure 3). Many optical fibers are supplied with an outer coating comprising a polymer jacket (acrylate, polyimide, or the like), and this jacket may be used as a mask provided it adheres

sufficiently to the optical fiber during etching. A preferred mask may comprise an outer fiber coating (shown as stippled shading in Figure 3) comprising a carbon coating. Optical fiber having a hermetic carbon outer coating (with or without a polymer jacket over the hermetic carbon coating) may be obtained commercially (Hermeticoat optical fiber, sold by Spectran Specialty Optics) or may be fabricated by deposition of a carbon layer on the fiber cladding (see for example U.S. Patent No. 5,281,247, said patent being hereby incorporated by reference in its entirety as if fully set forth herein). A carbon coating has been found to adhere very well to the optical fiber during etching of the optical fiber.

Whether the outer coating comprises a polymer jacket or a carbon film, the outer coating must be spatially patterned appropriately, thereby yielding a mask substantially covering the desired resonator fiber segment upon etching. The mask may preferably be patterned by spatially selective laser machining of the outer coating, removing the outer coating from the adjacent fiber segments and leaving the outer coating on the resonator fiber segment. A polymer jacket outer coating may be laser machined using a UV-emitting excimer laser. A carbon film outer coating may be laser machined using a pulsed laser (presumably ablatively) or with a substantially continuous laser (presumably thermally). During laser machining to pattern the mask the optical fiber may preferably be rotated about its long axis to produce ring-like mask patterns on the fiber. This rotation should preferably be quite concentric (thereby substantially minimizing any "orbital" motion of the fiber cross-section about the rotation axis, also referred to as centration error). This may preferably be achieved by using a capillary tube or fiber ferrule to align the fiber for rotation and laser machining. (Hereinafter, use of a capillary for fiber alignment as described herein shall be understood to equivalently encompass use of a fiber ferrule). A capillary tube should be chosen having an inner diameter closely matching the optical fiber diameter. For example, the Hermeticoat fiber mentioned hereinabove has a nominal diameter of 125 μm. Capillary tubing is commercially available (0.4 lambda supplied by Drummond Scientific, Inc.) having an inner diameter of 126.4±0.3 μm, making it ideal for concentrically aligning and rotating the fiber during laser machining. This capillary or fiber ferrule alignment technique for substantially concentric rotation of the optical fiber may be employed during any other fabrication step requiring such rotation of the optical fiber, as set forth hereinbelow. Similar use of a capillary for substantially concentric rotation of an optical fiber during laser processing is described in a publication of Presby et al. (Applied Optics **29** 2692 (1990)), said publication being

hereby incorporated by reference in its entirety as if fully set forth herein. While remaining within the scope of inventive concepts disclosed and/or claimed herein, any suitable means may be employed for substantially concentric rotation of the optical fiber during laser machining, including but not limited to a capillary tube, a fiber ferrule, an alignment chuck, an alignment jig, an indexed fiber holder, and so forth.

In a preferred method for precisely machining rings in a hermetic carbon mask material, the carbon coated fiber may be threaded through a first capillary tube (the alignment capillary). A relatively long segment of the carbon coated fiber (as long as several inches or more) may extend from the first end of the capillary, and is coupled to a rotation device. The rotation device must produce controlled, substantially uniform rotary motion of the fiber with minimal thrust error. (The term "thrust error" refers to any unwanted longitudinal motion that may accompany the desired rotary motion. The thrust error results in a tilt of the machined ring with respect to a plane perpendicular to the fiber axis, an effect which may be used to intentionally produce tilted rings. Provided that the thrust error is kept small, less than about 10% of the ring diameter, the ring tilt will not result in substantial undesirable radiative loss from the ring segment. Control of the tilt may be exploited to tune the resonant frequency of a ring fabricated from an optical fiber of a given diameter, since the perimeter path length, and hence the optical resonance frequencies, of the ring can be varied by varying the ring tilt angle by adjusting the thrust "error"). A prototype system (Figure 4) has been successfully constructed using a precision drill press 400 (Cameron Micro Drill) with the carbon coated fiber 402 cemented within a second capillary tube 404 and the second capillary tube held within the chuck 406 of the drill press 400. Without departing from inventive concepts disclosed and/or claimed herein, other devices may be equivalently employed to produce the desired rotary motion, including but not limited to rotation stages, stepper-motor-driven rotators, servo-motor-driven rotators, and the like. As the drill press or other rotary device rotates the carbon-coated fiber, the fiber rotates within the first capillary tube 408 with low centration error. As long as both fiber and alignment capillary are substantially uncontaminated, this rotation of the fiber within the capillary will not damage the carbon coating. If desired, it may be possible to drive air or other gas through the capillary around the rotating fiber to serve as an air-bearing. The alignment fiber is substantially rigidly mounted in a standard fiber chuck or other similar device 409, and a relatively short segment of the carbon-coated fiber 402 extends beyond the second end of the alignment capillary 408. A

microscope objective 410 (60X in the prototype; others may be used as appropriate) for delivering a laser beam for laser machining may be mounted on a precision 3-axis translator 412 for precise positioning relative to the carbon-coated fiber.

A laser beam 414 from an argon ion laser (typically multi-line visible output, mainly 488 nm and 514 nm, between about 50 mW and about 100 mW average power) is brought to a spot size between about 2 μm and about 3 μm, preferably about 2.5 μm, by the objective 410 onto the surface of the fiber 402 as it rotates, thereby removing the carbon coating from the fiber (presumably by a thermal mechanism). A beamsplitter 416 in the laser beam path allows back-scattered and/or back-reflected laser light from the fiber to be imaged at 418 in order to adjust the focus of the laser beam sufficiently precisely relative to the surface of the fiber. The laser beam need not necessarily be focused at the surface of the fiber (although it could be, if desired). Use of a microscope objective is important for several reasons. The highly convergent beam enables the machining of rings in the hermetic carbon coating as small as 1 to 3 μm wide with relatively sharp edges, which in turn reduces the roughness of the edges of the resonator fiber segment produced by subsequent etching. A tight focus on the machined surface of the fiber also insures that the laser beam transmitted through the fiber will be sufficiently defocused when it reaches the opposite surface of the fiber so that none of the coating will be removed from the opposing surface, which would degrade the precision of the edges of the machined rings. The centration error of the carbon-coated fiber within the capillary tube is typically sub-micron, well within the depth-of-focus of the tightly focused laser beam (typically a few microns). It has also been observed that microscopic defects may occur in the portions of the carbon coating left behind by after laser machining, resulting in unwanted etched spots in the resonator fiber segment and degradation of the performance of the resulting WGM resonator. It is speculated that hot ejecta from the laser machining may land on adjacent areas (where machining is not desired) and damage the carbon coating. It has been observed that flowing gas (O_2, N_2, and ambient air have been used successfully, although O_2 may be preferable) around the fiber as it is machined seems to substantially eliminate this problem.

It should be noted that a microscope objective may not be required for sufficiently precise machining of rings in the carbon coating. In general, if the optical fiber is substantially transparent to the wavelength used for machining the carbon coating (or other fiber outer coating), then the beam must be highly convergent (with an objective or similar optical assembly having an NA

greater than about 0.3, preferably around one) so that the transmitted beam is too large to damage the fiber outer coating on the opposite side of the fiber. However, if the fiber is not transparent to the laser-machining wavelength (157 nm from an F_2 excimer laser, for example, or if the fiber is a hollow fiber filled with material non-transparent at the laser-machining wavelength, or if the fiber is doped to render it non-transparent at the laser-machining wavelength), then damage to the opposite side of the fiber is no longer an issue, and the optical assemblies having longer working distances (i.e., smaller NA) may be employed. This is a general principle that may be applicable to other laser-machining steps set forth hereinbelow. Any laser source suitable for laser machining (known in the art or hereafter developed) may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein, for any laser machining step disclosed herein.

For silica or silicate-based optical fibers, aqueous hydrofluoric acid (HF) is an effective etching agent for removal of material from the adjacent segments of the optical fiber. The amount of material removed can be precisely controlled by controlling the etching time, etchant concentration and/or pH, and/or temperature. The etched surfaces are quite smooth and substantially free of irregularities, thereby minimizing optical scatter from the etched surfaces of the WGM optical resonator. It should be noted that as the etching process proceeds radially, exposure of transverse edges of the resonator fiber segment become exposed to the etchant and come under attack. The thickness of the resulting resonator fiber segment is therefore somewhat smaller than the width of the initial ring-shaped mask, and the edge of the resonator fiber segment may be slightly concave, particularly near the bottom of the edge where the resonator fiber segment joins the adjacent fiber segment. The concentration of HF used to etch the optical fiber may be between about 5% and about 50% HF buffered with NH_4F, should preferably be between about 7% and about 8% HF and between about 30% and about 40% NH_4F, and most preferably about 7.2% HF and 36% NH_4F. The most preferred concentration yields an etch rate of about 80 nm/min, and is available commercially (Transene Company, Inc.). Another suitable HF concentration is 1 part 40% HF(aq) combined with 10 parts 40% NH_4F(aq), as disclosed in the publication of Eisenstein et al. (Applied Optics **21** 3470 (1981), said publication being incorporated by reference in its entirety as if fully set forth herein. Any of these disclosed concentrations may be employed during any other fabrication step requiring an HF etch, as set forth hereinbelow. While remaining within the scope of inventive concepts disclosed and/or claimed herein, any suitable wet or chemical etching agent (either known in the art or hereafter

developed) may be used to reduce the diameter of the adjacent fiber segments or other portions of the fiber. Alternatively, dry or reactive ion etching procedures, employing suitable etch masks (metal masks or polymer masks, for example), may be used to reduce the diameter of the adjacent fiber segments or other portions of the fiber. After etching, the mask may be removed by any of a variety of methods, including but not limited to non-spatially-selective laser machining, chemical/solvent removal, thermal removal (i.e., burning), exposure to an electrical discharge, plasma ashing, ion sputtering, and other suitable methods for removing the mask (known in the art or hereafter developed).

As an alternative to the mask-and-etch procedure described hereinabove, the diameters of the adjacent fiber segments may be reduced by direct laser machining of the fiber to remove optical fiber material (Figure 5). Substantially concentric rotation may preferably be employed during laser machining using a capillary tube as described hereinabove. Laser machining may be performed without removing a fiber jacket (if present), in which case the fiber jacket is removed from the adjacent fiber segments during laser machining and the portion of the jacket remaining on the resonator fiber segments may be removed after laser machining by any appropriate method. Alternatively, the fiber jacket (if present) may be removed from the resonator fiber segment and the adjacent fiber segments prior to laser machining. A fluorine excimer laser emitting at 157 nm may preferably be used for laser machining a silica or silicate-based optical fiber, although other appropriate laser sources (pulsed UV-emitting laser sources, amplified and/or modelocked titanium:sapphire lasers, pulsed CO_2 lasers, and so forth) may be employed (particularly for other types of optical fiber) while remaining within the scope of inventive concepts disclosed and/or claimed herein. The earlier discussion of a low NA laser-beam-delivery optical assembly (if the fiber is substantially opaque at the laser-machining wavelength) versus a high NA laser-beam-delivery optical assembly (if the fiber is substantially transparent at the laser-machining wavelength) applies to direct machining of the optical fiber (a high NA assembly, i.e., a microscope objective, is shown in Figure 5 and is exemplary only). Following laser machining the fiber, including the resonator fiber segment and the adjacent fiber segments, may be polished to reduce and/or eliminate laser-machining-induced irregularities on the WGM resonator. Such irregularities may act as light scattering centers, thereby degrading the performance (Q-factor, for example) of the WGM resonator. Suitable polishing techniques may include but are not limited to

spatially non-selectively etching, thermal polishing with a flame or CO_2 laser, polishing with an electrical arc or fusion splicer, and so forth.

Once the adjacent fiber segments have been reduced in diameter relative to the resonator fiber segment, the diameter of the resonator fiber segment may be reduced to achieve a desired WGM resonant frequency and/or a desired free spectral range between modes, while producing a diameter of the resonator fiber segment 100 the desired amount larger than the diameter of the adjacent fiber segments 200. The free spectral range of the WGM resonator should preferably be between about 1 GHz and about 5 THz, and most preferably between about 500 GHz and about 2 THz. The desired free spectral range will be determined by the wavelength spacing of channels in the particular WDM standard in use and the number of these channels desired to be modulated by an optical power control device employing WGM resonator according to the present invention. The WGM free spectral range divided by the channel spacing yields the approximate number of channels that may be simultaneously modulated by a single device or a series of devices on a single transmission optical fiber. These free spectral ranges require a resonator fiber segment diameter between about 10 μm up to several millimeters, and preferably between about 25 μm and about 125 μm. Resonator fiber segment diameters below about 10 μm may result a WGM resonator Q-factor that is unacceptably low. The thickness of the resonator fiber segment should preferably be between about 1 μm and about 10 μm, and most preferably between about 1 μm and about 5 μm. The diameter of the resonator fiber segment may be reduced by spatially non-selective etching, employing aqueous HF (as described hereinabove) or other suitable etching agent (Figure 6). This may also reduce the thickness of the resonator fiber segment by etching the edges of the resonator fiber segment, and the resulting edges may be slightly concave (as described earlier). Alternatively, the diameter of the resonator fiber segment may be reduced by laser machining as described hereinabove and shown in Figure 5 (and may preferably include use of a capillary tube or fiber ferrule for substantially concentric rotation of the optical fiber during laser machining, as described hereinabove). Relatively fine-tuned selection of the WGM resonator diameter and/or thickness may be required to select a particular wavelength component from among the wavelength components present in a wavelength-division-multiplexed (WDM) optical signal. For example, to fabricate a WGM resonator selectively resonant with a single channel (typically about 10 GHz wide, for example) from among the 50 GHz- or 100 GHz-spaced WDM channels present within the ca. 80 nm overall bandwidth of the erbium amplifier C and L bands

(centered around 1550 nm), the diameter must controlled to within about ±5 nm (±10 GHz for the resonator frequency), requiring control of the etch time on the order of about ±1 second to about ±10 seconds. Such precision of fabrication may be readily achieved using standard techniques of laser machining or other precision machining methods, or by careful control of etch conditions (etchant concentration and/or pH, temperature, and/or etching time). Appropriate dilution of the etchant may yield slower etch rates, thereby enabling enhanced precision for the final diameter of an etched resonator fiber segment.

Alternatively, a desired WGM resonant frequency may be obtained by fabrication of a suitably tilted resonator fiber segment as set forth hereinabove. The resonant frequency shift varies as $\sin^2\theta$, where θ is the angle between the tilted ring and a plane perpendicular to the longitudinal axis of the optical fiber. Controlled longitudinal motion of the fiber during rotation as the fiber is machined may be employed to impart the desired tilt angle on the resonator.

It should be noted, however, that stable operation of a resonant optical power control device according to the present invention may require temperature stabilization of the WGM resonator. It has been observed that the resonance frequencies of a WGM resonator based on silica microsphere varies with temperature by about 2.5 GHz/°C, and presumably a similar quantity (modified by the appropriate geometric factor) applies to disk or ring WGM resonators fabricated from silica optical fiber according to the present invention, thereby necessitating control of the WGM temperature. However, this also affords the opportunity to control the resonant wavelength of the WGM resonator by varying the temperature at which the WGM resonator is maintained/stabilized. This may be accomplished with no substantial additional cost or complexity, since temperature stabilization is required even if temperature tuning of the resonant frequencies is not desired. Any suitable method for monitoring and controlling the WGM temperature (known in the art or hereafter developed) may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. A thermo-electric cooler may be well-suited for controlling the resonator temperature, although other temperature control devices may serve as well.

Instead of decreasing the diameter of the adjacent fiber segments, the resonator segment may alternatively be enlarged by deposition of a substantially annular ring of material on the optical fiber. This may preferably be accomplished by the process of: 1) providing the adjacent

fiber segments with a mask while leaving the resonator fiber segment substantially exposed; 2) spatially-selectively depositing material on the resonator fiber segment, thereby increasing its diameter; and 3) removing the mask from the adjacent fiber segments (Figure 7). Related techniques are disclosed in the following publications: Frolov et al., Applied Physics Letters, 72 2811 (1998); Frolov et al., Applied Physics Letters 72 1802 (1998); Kuwata-Gonokami et al., Optics Letters 20 2903 (1995); and Kawabe et al., Applied Physics Letters 72 141 (1998). Each of these publications is incorporated by reference in its entirety as if fully set forth herein. In particular, it may be preferred to provide the mask by spatially-selective removal of an outer coating 300 of the optical fiber from the resonator fiber segment. This spatially-selective removal of the outer coating of the optical fiber may be performed by laser machining as already described herein and shown in Figure 5. The outer coating of the fiber may comprise the polymeric jacket of the fiber, or may comprise any suitable mask material deposited on the fiber prior to the mask-providing step. A UV-emitting excimer laser may preferably be employed for laser machining of the polymeric jacket, although any other suitable laser source may be employed for laser machining a particular mask material. The fiber may be rotated during laser machining and may be mounted in a capillary to provide substantially concentric rotation, as already described elsewhere herein.

As shown in Figure 7, once the mask has been provided substantially covering the adjacent fiber segments while leaving the resonator fiber segment 100 substantially exposed, material 310 may be spatially-selectively deposited on the resonator fiber segment by any of a variety of suitable techniques. Chemical vapor deposition (CVD) may be a preferred deposition technique, although other techniques may be employed (often depending on the nature of the material being deposited) while remaining within the scope of inventive concepts disclosed and/or claimed herein. Such techniques may include but are not limited to: deposition of self-assembled monolayers (SAM's), thermal evaporation/deposition, sputter deposition, epitaxial techniques, combinations thereof, and/or functional equivalents thereof. The fiber may preferably be rotated during deposition of the material, thereby resulting in substantially uniform deposition of material around the circumference of the optical fiber. The fiber may be mounted within a capillary tube or fiber ferrule, thereby enabling substantially concentric rotation of the fiber for substantially uniform deposition. After deposition of the material 310, the mask (i.e., outer coating 300) may be removed by any suitable mechanical, chemical, optical, or other process suitable for the

particular mask employed. The deposited material 310 forms a substantially annular ring on the circumference of the optical fiber, and eventually forms at least a portion of the whispering-gallery-mode optical resonator fiber segment 100.

A dielectric material may typically be preferred as the deposited material. Suitable materials may include, but are not limited to: silica, germano-silicate, semiconductor-doped glasses, amorphous semiconductors, chalcogenide glasses, amorphous silicon alloys, combinations thereof, and/or functional equivalents thereof. It may be preferred to use a material having substantially fixed optical properties (silica, for example), thereby yielding a WGM resonator having substantially fixed properties. Alternatively, it may be desirable to deposit material that enables subsequent modification an/or modulation of the WGM resonator properties. Such a material may comprise a pure material, a mixture of materials, a secondary material deposited as a thin film coating on a primary material, and/or a primary material having one or more secondary materials as dopants therein. Materials may be selected, designed, and/or formulated to enable controlled modulation of optical properties of the WGM resonator, including but not limited to: optical loss, optical gain, optical coupling to/from the WGM resonator, resonant frequencies, free spectral range, and so forth. The materials used may include, but are not limited to: dielectric materials, electro-optic materials, electro-absorptive materials, non-linear optical materials, semiconductor materials, metals, polymers, combinations thereof, and/or functional equivalents thereof. Application of electronic, optical, and/or other control signals to the WGM resonator may be employed for modulation of one of more of the WGM optical properties.

Following deposition of material resonator fiber segment to form the WGM resonator, the diameter of the WGM resonator may be reduced by removal of material to alter resonant frequencies and/or the free spectral range of the WGM resonator using etching, laser machining, and/or other suitable techniques as already described herein (Figure 6). Preferred ranges for resonator fiber segment diameter, thickness, and free spectral range have been given hereinabove.

The refractive index of the fiber may be the property that differs between the resonator fiber segment and the adjacent fiber segments. A transverse resonator fiber segment having a refractive index as little as 10^{-4} greater than the refractive index of the adjacent fiber segments may enable confinement of a WGM optical wave propagating around the circumference of the resonator fiber segment at least partially within the fiber segment. The refractive index of the

resonator fiber segments may be increased by spatially-selectively increasing the density of the resonator fiber segment, or the chemical composition of the resonator fiber segment may be spatially-selectively altered to yield a larger refractive index. Generation of this refractive index differential may be accomplished while producing fewer irregularities (such as arise during laser machining) on the optical fiber that could lead to scattering during use of the device and degradation of the performance characteristics of the WGM resonator (such as the resonator Q-factor).

Densification of germano-silicate material by UV-irradiation is well known, and has been previously used to generate periodic variations in the refractive index of the germano-silicate core of optical fibers to produce fiber Bragg gratings (also known as distributed Bragg reflectors). In a method for fabricating a WGM resonator according to the present invention, the optical fiber is a germano-silicate fiber or other UV-sensitive optical fiber, and the resonator fiber segment 100 is spatially-selectively irradiated with UV light, thereby densifying the resonator fiber segment 100 and increasing its refractive index relative to the adjacent fiber segments 200 (shown in cross-section in Figure 8A, where the density of the stippled hatching reflects the relative refractive index, density, and/or a dopant concentration). A UV-emitting excimer laser may be particularly well-suited for this purpose, however, any suitable UV source sufficiently intense and/or focusable may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein, including but not limited to an ArF excimer laser (193 nm), a KrF excimer laser (248 nm) and an argon ion laser (334 nm). Various masks 810 may be employed to obtain the desired spatial variation of refractive index, including phase masks and amplitude masks. Such techniques are disclosed in: Starodubov et al., Optics Letters, **22** 1086 (1997); Hill et al., Applied Physics Letters, **62** 1035 (1993); and Hill et al., Optics Letters, **19** 1314 (1994). Each of these publications is hereby incorporated by reference in its entirety as if fully set forth herein. Alternatively, the spatially selective irradiation may be accomplished without masking, but by controlling the spatial profile of the irradiating beam (see discussion above pertaining to high NA and low NA optical assemblies). The fiber may be rotated during irradiating, and a capillary or fiber ferrule may be employed to mount the fiber and provide substantially concentric rotation as described earlier herein. The densification need not necessarily extend all the way through the fiber (as shown in Figures 8A, 8B, and 8C), but may comprise a ring of densified fiber material around the circumference of the resonator fiber segment. The susceptibility of germano-silicate

to densification by UV irradiation may be enhanced by hydrogen loading the germano-silicate material prior to UV irradiation. This may be accomplished by exposing the germano-silicate optical fiber to about 2500 psi of H_2 gas for a period of about one week, for example. Other H_2 pressures and exposure times may also be suitable. Germano-silicate fiber of a sufficiently large diameter (greater than about 50 μm, for example) for fabricating WGM resonator according to the present invention may be obtained commercially, or may be produced by stripping the lower index cladding material from a multi-mode germano-silicate-core optical fiber. Such multi-mode fibers may have core diameters of about 50 μm or more, so that stripping the cladding may leave a fiber having a diameter sufficiently large to produce the WGM resonator therefrom. The cladding may be stripped by any suitable means, including but not limited to laser machining (possibly utilizing a capillary for mounting and substantially concentrically rotating the optical fiber during laser machining) and etching (with aqueous HF or other suitable etching agent).

The refractive index of the resonator fiber segment relative to the adjacent fiber segments may alternatively be spatially-selectively increased by altering the chemical composition of the resonator fiber segment by a method comprising the steps of: 1) providing a mask that substantially covers the adjacent fiber segments while leaving the resonator segment substantially exposed; 2) doping the resonator fiber segment with a suitable doping material; and 3) removing the mask from the adjacent fiber segments (Figure 8A). The same methods described hereinabove for producing masks for spatially-selective deposition of material onto the fiber may also be employed for producing a mask for spatially-selective doping of the optical fiber, including use of an outer coating of the optical fiber as the mask material 810. Alternatively, the outer coating may instead be spatially-selectively removed from the adjacent fiber segments 200 and left on the resonator fiber segment 100, and the mask material 810 may then be deposited onto the adjacent fiber segments 200. The resonator fiber segment 100 may then be spatially-selectively doped after removal of the remaining outer coating therefrom. The mask material 810 may be a metal, a dielectric material, a polymer mask, or other suitable material.

After providing the mask on the adjacent fiber segments, the resonator fiber segment may be doped in any of a variety of suitable techniques, including but not limited to: ion implantation of the doping material into the fiber; and simple diffusion of the doping material (by exposure of the masked fiber to dopant vapor or liquid; or by deposition of solid dopant onto the masked fiber) into the optical fiber. As in various deposition and laser machining steps described

hereinabove, the optical fiber may be rotated during the doping step to obtain substantially uniform doping of the optical fiber around its circumference, and the fiber may be mounted in a capillary tube to provide substantially concentric rotation of the fiber during doping. The doped region need not necessarily extend all the way through the fiber (as shown in Figures 8A, 8B, and 8C), but may comprise a ring of doped fiber material around the circumference of the resonator fiber segment. The fiber may be doped with any of a variety of suitable materials for increasing the refractive index of the optical fiber while remaining within inventive concepts disclosed and/or claimed herein. Preferred materials for use as the doping material include but are not limited to germanium, titanium, boron, aluminum, phosphorus, erbium, ytterbium, praseodymium, thulium, holmium, neodymium, and other rare earth elements. In addition to altering the refractive index of at least a portion of the resonator fiber segment, an appropriately chosen doping material may comprise a material than enables modification of the optical properties of the WGM resonator, such properties including optical loss, optical gain, optical coupling to/from the resonator, and resonant frequencies. Such doping materials may include but are not limited to: electro-optic materials, electro-absorptive materials, non-linear optical materials, semiconductor materials, combinations thereof, and/or functional equivalents thereof. Such doping materials may be used to modulate optical properties of the WGM resonator by application of optical, electronic, and/or other control signals to the WGM doped with the doping material.

Following the increase of the refractive index of the resonator fiber segment to form the WGM resonator (whether produced by densification or doping), the diameter of the WGM resonator may be reduced by removal of material to alter resonant frequencies and/or the free spectral range of the WGM resonator using etching, laser machining, and/or other suitable techniques as already described herein (Figure 8B). Preferred ranges for resonator fiber segment diameter, thickness, and free spectral range have been given hereinabove.

In addition to producing a WGM resonator fiber segment by spatially-selectively increasing the refractive index, spatially-selective doping may be employed to produce a WGM resonator by an alternative technique (Figure 8C). Certain dopants (germanium, for example) are know to decrease the etch rate of silica. By spatially-selectively doping a resonator fiber segment 100 of a silica fiber with germanium prior to etching, a relatively larger-diameter resonator fiber segment 100 is produced by the etching process, since the adjacent fiber segments 200 are etched at a faster rate. Careful control of the germanium doping level and the etching conditions

(concentration, pH, temperature, etching time, and so forth) allow control over the properties of the resulting WGM resonator fiber segment.

In a typical application of a resonant optical power control device according to the present invention, the WGM resonator is optically coupled to a second optical fiber (also referred to herein as a "transmission optical fiber") in order to enable control of transmission of optical power through the second optical fiber. In a preferred embodiment of a resonant optical power control device according to the present invention, the WGM resonator and a second optical fiber are positioned on an alignment device to enable optical coupling between the second optical fiber and the WGM resonator. Reproducible optical coupling between the second optical fiber and the resonator is highly desirable to enable efficient and consistent fabrication of the resonant optical power control device. Accordingly, the WGM optical resonator may preferably be provided with an alignment structure (alternatively referred to as an "indexing structure") on at least one of the adjacent fiber segments 200 for enabling reproducible optical coupling of the resonator fiber segment 100 and the second optical fiber when they are positioned on the alignment device. Preferred alignment or indexing structures that may be provided on one or more of the adjacent fiber segments 200 may comprise circumferential grooves 220 and/or circumferential annular flanges 210 for engaging corresponding alignment or indexing structures that may be provided on the alignment device (Figures 9A and 9B). Other suitable alignment or indexing structures may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. Flanges 210 and/or grooves 220 may be fabricated by spatially-selective deposition and/or removal of material from the optical fiber. A groove may be produced by removing material from the groove location, or alternatively by depositing material on each side of the groove location. A flange may be produced by depositing material on the flange location, or alternatively by removing material from each side of the flange location. Spatially-selective deposition and/or removal of material to produce flanges, grooves, and/or other alignment structures may be performed by laser machining, masking, etching, and/or other suitable methods as already set forth hereinabove. Deposited material may comprise the same material as the adjacent fiber segment, and/or any other material suitable for depositing on the adjacent fiber segment a having properties suitable for use as an alignment structure (for example, mechanical strength, adhesion to the adjacent fiber segment, chemical compatibility, and so forth). Examples may include but are not limited to: outer coating material of the fiber, fiber jacket material (polymeric jacket material, for example),

fiber cladding material, fiber core material, and/or other functionally equivalent materials. Material removed from the fiber may comprise portions of: an outer coating material of the fiber, fiber jacket material (polymeric jacket material, for example), fiber cladding material, and/or fiber core material.

To enable controlled modulation of optical properties of the WGM resonator, a modulator may be provided on at least one of the resonator fiber segment and the adjacent fiber segments. Preferably, a modulator material may be deposited on the resonator fiber segment or at least one of the adjacent fiber segments so that at least a portion of the deposited modulator material lies within at least a portion of the whispering-gallery-mode optical wave confined by the resonator fiber segment. The modulator material may be used to modulate optical properties of the WGM resonator by application of optical, electronic, and/or other control signals to the modulator material. Modulated properties of the WGM optical resonator may include optical loss, optical gain, optical coupling to/from the WGM resonator, resonant frequencies, free spectral range, and so forth. Materials that may be employed as the modulator material may include, but are not limited to: electro-optic materials, electro-absorptive materials, non-linear optical materials, semiconductor materials, combinations thereof, and/or functional equivalents thereof.

The modulator material 552 may be provided on the circumference of the resonator fiber segment 100, or at least a portion of the circumference, so that at least a portion of the modulator material lies within at least a portion of the WGM optical wave confined by the resonator fiber segment (Figure 10). In particular, an evanescent wave portion of the WGM optical wave may extend radially outward from the circumference of the resonator fiber segment and thus encompass modulator material deposited thereon. Altering the properties of the modulator material thus encompassed in turn affects the confined WGM optical wave.

Alternatively, the modulator may be provided by truncating one of the adjacent fiber segments 200 to create a fiber end-face 230 so that at least a portion of the end-face is encompassed by the WGM optical wave confined by the resonator fiber segment. The modulator material 554 may be provided on the encompassed portion of the end-face (Figure 11). In particular, if the portion of the adjacent fiber segment remaining after truncation is sufficiently short, the end-face and modulator material thereon will lie within at least part of an evanescent wave portion of the WGM optical wave extending longitudinally from the resonator fiber

segment. Altering the properties of the modulator material thus encompassed in turn affects the confined WGM optical wave. A preferred modulator material may comprise a semiconductor quantum well material that may be optically or electro-absorptively controlled to control the optical loss of the WGM optical wave, thereby altering the WGM resonator Q-factor and modulating transmission of optical power through the transmission optical fiber.

In a resonant optical power control device according to the present invention, the WGM resonator is coupled to a transmission optical fiber. Optical signals to be controlled propagate through the transmission optical fiber, where they may be controlled, modulated, and/or re-routed by application of control signals to the control device. The transmission optical fiber may be adapted to allow optical coupling of a WGM to the optical wave propagating through the transmission optical fiber, thereby enabling controlled modulation and/or re-routing of the optical signal propagating through the transmission optical fiber by altering one or more optical properties of the WGM resonator. Such optical power control devices and control, modulation, and/or re-routing techniques are described in detail in: U.S. provisional application Serial No. 60/111,484; U.S. application Serial No. 09/454,719; U.S. provisional application Serial No. 60/108,358; and U.S. application Serial No. 09/440,311. Each of these applications has been incorporated herein by reference.

In order to achieve and maintain reliable, reproducible, and stable optical coupling between a transmission optical fiber and a WGM resonator during and after manufacture of a resonant optical power control device according to the present invention, an alignment device 500 may be employed (Figure 12). Such an alignment device may comprise a first alignment substrate 502 having a fiber-alignment groove 506 and a resonator-alignment groove 504 thereon. A method for fabricating a resonant optical power control device according to the present invention comprises the steps of: 1) positioning and securing a transmission optical fiber 600 within the fiber-alignment groove 506; and 2) positioning and securing the WGM optical resonator 100 (as described hereinabove, or of some other functionally equivalent configuration) within the resonator-alignment groove 504. The fiber-alignment groove 506 and resonator-alignment groove 504 may be positioned on the alignment substrate 502 so that when positioned and secured therein, the transmission optical fiber 600 and the WGM resonator 100 are in substantial tangential engagement (usually mechanical contact between the fiber and the circumference of the resonator; see below and Figure 13), thereby optically coupling the WGM resonator to the

transmission optical fiber. Optical coupling between the WGM resonator and the transmission optical fiber may be achieved as long as at least part of the evanescent wave portions of each of the whispering-gallery-mode of the resonator and the propagating mode of the fiber are spatially overlapped. The degree of overlap and the degree of phase matching determines the degree of optical coupling between the resonator and the fiber. Actual mechanical contact is not required, only that the resonator and fiber be sufficiently close to permit the overlap. However, in a preferred embodiment of an optical power control device according to the present invention, optical coupling between the resonator and the fiber is most reproducibly, reliably, and stably achieved by positioning and securing the WGM resonator and the transmission optical fiber in mechanical contact with one another within each respective alignment groove.

As shown in Figure 12, the resonator-alignment groove and the fiber-alignment groove may preferably be substantially perpendicular, so that the fiber and WGM resonator may be substantially co-planar. The alignment grooves may have substantially constant width and depth profiles along their respective lengths, or alternatively may have tailored width and/or depth profiles. The cross-sectional shape of the alignment grooves may preferably be substantially rectangular (in fact probably slightly trapezoidal due to laser machining), but may alternatively have any suitable cross-sectional shape suitable for positioning and securing the WGM resonator and the transmission optical fiber. The depths of the resonator-alignment groove and fiber groove are preferably chosen so that when positioned and secured therein, the fiber and WGM resonator are in direct contact and therefore optically coupled in a reproducible, reliable, and stable manner (Figure 13). The depths chosen depend on the mechanical configurations of the WGM resonator and the transmission fiber, as may be readily determined for a particular configuration by one skilled in the art. Either the fiber-alignment groove or the resonator-alignment groove may be the deeper groove, and typically the component (fiber or resonator) corresponding to the deeper groove is positioned and secured in its respective groove first, and the other component positioned and secured after the first, although this need not always be the case. For example, if a plurality of WGM resonators are to be coupled to a single transmission optical fiber, it may be preferable to tangentially engage the transmission optical fiber alternately (by ones or twos) from opposite sides to ensure reproducible optical coupling with all of the WGM resonator. It may be desirable in this instance to provide a first alignment substrate with alignment grooves on opposing faces thereof, thereby allowing access to opposing sides of a

transmission optical fiber positioned within a fiber alignment groove thereof. Alternatively, alignment grooves may be provided at at least three operational depths: a deepest set of one or more resonator-alignment grooves, an intermediate fiber-alignment groove, and a shallowest set of one or more resonator-alignment grooves (Figure 14). Any of a variety of functionally equivalent methods may be employed for securing the transmission optical fiber and/or the WGM resonator within the respective alignment groove, including but not limited to: application of adhesives, epoxies, resins, polymers, solders, and the like; welding or fusing; and providing a mechanical retainer for retaining the transmission fiber and/or WGM resonator within the respective alignment groove, such as a clamp, clip, fastener, plate, or other like device. In an alternative embodiment of an optical power control device, the transmission optical fiber may be fused or welded (with a CO_2 laser, for example) to the circumference of a WGM resonator to insure stable, reliable, and reproducible optical coupling. Once the transmission optical fiber and WGM resonator have each been positioned and secured within the respective alignment groove, the alignment device may be sealed (preferably hermetically sealed) to isolate the fiber and resonator from the use environment of the optical power control device. This is important for a number of reasons. First, the optical coupling relies on the propagation of evanescent optical waves from free surfaces of the transmission fiber and WGM resonator. Any contamination of these free surfaces may drastically alter the optical properties of the fiber and/or resonator and/or optical coupling thereof, thereby altering the performance of the optical power control device. Similarly, any movement of the transmission optical fiber relative to the WGM resonator may also alter the optical coupling and performance of the control device. The alignment device may comprise a cover, second substrate, or other functionally equivalent component 508 that may be positioned over the alignment grooves and sealed into place (using adhesives, epoxies, resins, polymers, solders, and/or the like; or using welding or fusion), leaving the two ends of the transmission optical fiber exposed for connecting to an optical power transmission system (Figure 15).

In a preferred embodiment of a optical power control device according to the present invention, a WGM resonator is employed having been fabricated from an optical fiber as disclosed hereinabove. Such a WGM resonator fabricated from an optical fiber and comprising a resonator fiber segment and adjacent fiber segments may be particularly well-suited for use in the optical power control device fabrication methods described herein. The adjacent fiber segments may

serve to reproducibly, reliably, and stably position the WGM resonator within the resonator-alignment groove, particularly in directions substantially orthogonal to the longitudinal axis of the resonator fiber segment and adjacent fiber segments. Proper longitudinal positioning is required so that the transmission optical fiber 600 tangentially engages the resonator fiber segment 100 and not an adjacent fiber segment 200. This may be most simply accomplished by providing a blind resonator-alignment groove 504, truncating an adjacent fiber segment 200 at an appropriate length, and positioning the WGM resonator 100 in resonator-alignment groove 504 so that the truncated end of adjacent fiber segment 200 butts up against the blind end of resonator-alignment groove 504. If the truncated end is angle polished and the blind groove end is angled, rotation of the fiber may serve to adjust the lateral position of the WGM resonator. Alternatively, alignment structures provided on the adjacent fiber segments may serve to properly longitudinally position the WGM resonator within the resonator-alignment groove. Preferred alignment structures that may be provided on one or more of the adjacent fiber segments 200 may comprise circumferential grooves 220 and/or circumferential annular flanges 210 for engaging corresponding alignment structures (flanges 520 and/or grooves 510, respectively) that may be provided in the resonator-alignment groove 504 of the alignment device 500 (Figure 16). Details of fabrication of a WGM resonator having such alignment structures are disclosed hereinabove. Other suitable alignment structures may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein.

A major portion of the cost associated with manufacture of optical power control devices arises from the labor-intensive steps involved in properly aligning the components of the device. Often active alignment techniques are required wherein some measure of device performance (examples include insertion loss, modulation depth, bandwidth, and so forth) is monitored and optimized with respect to alignment of components of the device. Such active alignment steps are reduced or substantially eliminated from fabrication of a resonant optical power control device according to the present invention. In particular, appropriate depths chosen for the resonator-alignment groove and the fiber-alignment groove, and circumferential grooves and/or annular flanges provided on an adjacent fiber segment and appropriately positioned mating structures in the resonator-alignment groove for engaging the adjacent fiber segment, both serve to enable positioning the WGM resonator fiber segment in substantial tangential engagement (in mechanical contact, for example) with the transmission fiber when each is positioned within the respective

alignment groove, without any need for active monitoring of device properties during assembly and/or alignment. Such passive alignment techniques substantially reduce manufacturing time and cost, and substantially enhance reliability and consistency of the manufactured devices.

The transmission optical fiber may be adapted to facilitate optical coupling between an optical wave propagating along the transmission fiber and the WGM optical wave confined by the WGM resonator fiber segment. Such adaptation may typically involve modification of a portion of the transmission fiber so that a portion of the propagating optical wave exists as an evanescent wave extending radially beyond the circumference of the transmission fiber. Spatial overlap of the transmission optical fiber evanescent wave and an evanescent portion of the WGM optical wave is the source of optical coupling. One such modification to the transmission optical fiber may include the use of D-shaped optical fiber 600, in which the fiber has a D-shaped cross-section such that the fiber core 602 is sufficiently near to the flat side of the "D" that a traveling optical wave propagating along the fiber has an evanescent wave portion extending transversely beyond the flat side of the "D". Upon assembly of an optical power control device according to the present invention, the D-shaped transmission optical fiber and the WGM resonator fiber segment 100 may each be positioned and secured in respective alignment grooves 506 and 504 so that the resonator fiber segment 100 is in substantial tangential engagement (in mechanical contact, for example) with the flat portion of the "D", as shown in Figure 17. As described earlier herein, appropriate depths of the alignment grooves and mating alignment structures on the adjacent fiber segments and resonator-alignment groove may be employed to enable reproducible, reliable, and stable optical coupling of the WGM and the D-shaped transmission fiber without resort to complicated and/or labor-intensive active alignment procedures.

Alternatively, the transmission optical fiber 600 may be provided with a fiber taper segment 604. Such a taper may be provided, for example, in a single-mode optical fiber by heating a segment of the fiber while pulling on the ends of the fiber. For a typical single-mode fiber having an outer diameter (core plus cladding) of about 125 μm, for example, this procedure results in a smoothly varying fiber diameter which decreases from about 125 μm to about 1 μm to about 3 μm and then increases to about 125 μm. The smooth variation in fiber diameter permits virtually lossless transmission of a traveling optical wave along the fiber. However, the optical wave comprises a significant evanescent portion extending radially beyond the circumference of the narrow part of the taper. Upon assembly of an optical power control device according to the

present invention, the fiber taper segment of the transmission optical fiber and the WGM resonator fiber segment may each be positioned and secured in respective alignment grooves so that the resonator fiber segment is in substantial tangential engagement (in mechanical contact, for example) with the fiber taper segment, as shown in Figure 18. As described earlier herein, appropriate depths of the alignment grooves and mating alignment structures on the adjacent fiber segments and resonator-alignment groove may be employed to enable reproducible, reliable, and stable optical coupling of the WGM and the fiber taper segment without resorting to complicated and/or labor-intensive active alignment procedures.

As a further means for providing stable optical coupling between the fiber taper segment and the WGM resonator, the circumference of resonator fiber segment may be provided with a relatively shallow groove 110 for receiving the fiber taper segment 604, as shown in Figure 26. Such a groove serves to prevent fiber taper segment 604 from sliding over the edge of resonator fiber segment 110. The groove 110 may be provided on the circumference of resonator fiber segment by any of the means disclosed herein for providing grooves and/or flanges on an optical fiber, including mask/etch techniques, direct laser machining techniques, mask/deposition techniques, and so forth. The embodiment of Figure 14 may be modified to include such a circumferential groove 110 on each resonator fiber segment 100 for receiving/retaining/aligning fiber taper segment 604. In fact, one or more (up to a maximum of all less one) of resonator fiber segments 100 may be provided solely for the purpose of receiving/retaining/aligning fiber taper segment 604, and not to also function as optical resonators.

The fiber taper segment described hereinabove may often prove to be quite fragile, and may be subject to frequent breakage during assembly of an optical power control device according to the present invention. In addition to the general risk of breaking such a delicate object any time it is handled, there is also the particular risk of breakage while attempting to position and secure the transmission optical fiber including a fiber taper segment within the fiber-alignment groove. In order to enable reliable, reproducible, and stable alignment of the fiber taper segment and the WGM resonator fiber segment, the transmission optical fiber must fit into the fiber-alignment groove with rather tight tolerances (about ±1 μm). However, the resulting maneuvering required to position the transmission fiber within the fiber-alignment groove may often prove too strenuous for the delicate fiber taper segment. Therefore, in a preferred fabrication method according to the present invention (illustrated in Figure 19), a non-tapered

transmission optical fiber 600 may be positioned in the fiber-alignment groove 506. After such positioning, the transmission fiber 600 may then be heated (by a flame or CO_2 laser at the point where it crosses the eventual position of the WGM resonator) and pulled, thereby yielding a fiber taper segment 604. The fiber taper segment 604 is thereby already positioned within the fiber-alignment groove 506 without being subjected to breakage. The transmission optical fiber (and fiber taper segment thereof) may subsequently be secured within the fiber-alignment groove. In order to facilitate this *in situ* heating and pulling of the transmission fiber to generate a fiber taper segment, the fiber-alignment groove 506 may preferably be provided with an enlarged central portion 510, deeper and/or wider than the remaining end portions of the fiber-alignment groove 506. The enlarged portion of the fiber-alignment groove preferably corresponds to the eventual location of the fiber taper segment 604 and resonator fiber segment 100, and reduces or substantially eliminates mechanical and/or thermal contact between the alignment substrate 502 and the portion of the transmission optical fiber 600 that is heated and pulled to form the fiber taper segment 604. In this way, thermal and/or mechanical disturbances that may distort and/or degrade the fiber taper segment during heating and pulling may be reduced and/or substantially eliminated, thereby enabling reliable and reproducible production of the fiber taper segment. It may be desirable for the enlarged portion 510 of the groove 506 to extend through the alignment substrate 502 so that the flame or CO2 laser used to heat the fiber does not also heat and/or damage the alignment substrate 502.

Fiber tapers may be pulled from standard single-mode optical fiber or polarization preserving optical fiber, which typically has a cladding outer diameter of about 125 μm and a core diameter of between about 5 μm and about 10 μm. When heated and pulled to yield a fiber taper having the desired diameter (between about 1 and about 10 μm, preferably between about 1 μm and about 3 μm), the length of the taper section is typically about 10 to 20 mm in length, necessitating a relatively long fiber-alignment groove, and relatively large alignment substrate and alignment device. This relatively long fiber taper segment may also reduce the stability of the optical power control device, since the relatively long fiber taper segment may move within the enlarged portion of the fiber-alignment groove thereby changing the degree of optical coupling between the fiber taper segment and the WGM resonator. This problem may be mitigated, and the overall sizes of the fiber-alignment groove and alignment substrate reduced, by pre-thinning the transmission optical fiber before heating and pulling to produce a fiber taper segment. A 125

μm fiber may be pre-thinned by etching or heating/pulling to a diameter of about 50 μm. This fiber thickness is still sufficiently robust to withstand positioning with a fiber-alignment groove. Heating and pulling the pre-thinned fiber to a diameter of 2-3 μm may now be performed *in situ* without the need for an enlarged portion of the fiber-alignment groove and yielding a shorter (about 1 mm to about 5 mm) and therefore more mechanically stable fiber taper segment.

Whispering-gallery-mode optical (WGM) resonators and methods for fabrication thereof have been described hereinabove wherein the WGM resonator may be provided with a modulator for enabling controlled modulation of optical properties of the WGM resonator. The modulator may be provided in a variety of ways, including but not limited to: in a WGM resonator fabricated by providing material on the circumference of a resonator fiber segment, the material provided may enable modification of optical properties of the WGM resonator; in a WGM resonator fabricated by spatially-selective doping of a resonator fiber segment, the doped material may enable modification of optical properties of the WGM resonator; a modulator material may be provided on at least a portion of the circumference of the WGM resonator and therefore be encompassed by an evanescent portion of the WGM optical wave extending radially from the resonator fiber segment; an adjacent fiber segment may be truncated sufficiently close to the resonator fiber segment so that at least a portion of the resulting fiber end face is encompassed by a evanescent wave portion of the WGM optical wave extending longitudinally from the resonator fiber segment, and a modulator material may be provided on the portion of the fiber end face thus encompassed; combinations thereof; and/or functional equivalents thereof. The modulator material (including deposited, bonded, attached, and/or doped material) may include but is not limited to: an electro-optic material; an electro-absorptive material; a non-linear optical material; a semi-conductor material (including hetero-structures such as quantum wells); an optical gain medium (a laser material, for example); a piezo-electric material; combinations thereof; and/or functional equivalents thereof. The modulator may enable controlled modulation of one or more optical properties of the WGM resonator, including but not limited to: optical gain and/or loss; optical coupling to the WGM resonator; a resonant frequency of the WGM resonator; combinations thereof; and/or functional equivalents thereof.

For each of the various modulator structures, methods, and materials recited hereinabove for a WGM resonator, some sort of control signal must be applied to the modulator. A modulator control element may therefore be provided on the alignment device for providing such

signals to a modulator of a WGM resonator. Such signals may comprise an electronic control signal, an optical control signal, a mechanical control signal, and/or other control signal, and the modulator control element may comprise means for applying such control signals to the modulator. Examples of such means may include, but are not limited to: electrical conductors, wires, cables, electrodes, electrical contacts, ohmic contacts, wireless transmitters and/or receivers, semiconductors, semiconductor hetero-structures (including quantum wells), diodes, triodes, transistors, field-effect transistors (FET's), CMOS devices, integrated circuits, ASIC's, digital circuits, analog circuits, optical fibers, lenses, micro-lenses, mirrors, prisms, integrated optics, adaptive optics, light sources, laser sources, laser diodes, light-emitting diodes (LED's), photo-voltaic devices, photo-conductive devices, piezo-electric devices, electro-strictive devices, actuators, translators, rotators, linear and/or rotary stepper motors, linear and/or rotary servo systems, combinations thereof, and/or functional equivalents thereof. Several specific illustrative examples follow. An electronic and/or optical control signal may be applied to an optically thin semiconductor quantum well material provided on a fiber end face, for example, thereby altering the optical loss of the WGM resonator. An optical and/or electronic signal may be applied to an electro-optic material deposited on the resonator fiber segment, thereby altering the WGM resonator refractive index and therefore also altering a resonant frequency of the WGM resonator. A mechanical control signal may be applied via a piezo-electric control element to move a transmission fiber taper into or out of mechanical contact with the circumference of the WGM resonator, thereby altering the optical coupling between the WGM resonator and the transmission fiber taper. The foregoing are exemplary only, and many other modulation schemes may be devised for application of control signals for modulating of WGM resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein. A portion of the modulator control element may reside on and/or within the alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device.

In a preferred embodiment of the present invention (Figure 20), a modulator material may comprise a semiconductor quantum well material 702 grown on a substrate 700. For example, the active layer of the quantum well material may comprise an InGaAs with barrier layers comprising InGaAsP. The quantum well material may comprise a stacked, multi-quantum well material. Quantum well materials are described in detail in U.S. Patent Nos. 5,343,490 and

5,878,070, and each of said patents is incorporated in its entirety as if fully set forth herein. The quantum well material may be processed by lithography or other functionally equivalent technique to yield a "ring mesa" 704 (i.e., a projecting annular flat-topped structure) projecting from the substrate and having an outer diameter roughly corresponding to the diameter of a truncated adjacent fiber segment 200. The fiber end face may then be bonded (by wafer bonding, epoxy, cold welding, or other equivalent technique) to the ring mesa 704, after which the quantum well substrate 700 may be removed (by etching or other means), leaving an annular thin film of quantum well material on the fiber endface and at least partially encompassed by a WGM optical wave confined by the WGM resonator fiber segment 100 (Figure 21). Electrodes 706 and 708 may be connected to the quantum well thin film 704 to deliver electronic control signals. The electrodes may comprise thin gold films above (annular 708) and below (annular or preferably circular 706) the quantum well thin film (the film below being bonded to the fiber end face and the quantum well material in turn bonded to the gold film; such a film itself results in little optical loss for the WGM optical wave polarized substantially perpendicular to the film). If a hollow-core optical fiber is used for fabrication of WGM resonator 100, then gold film 708 and quantum well thin film 704 need not be annular (as in Figures 20 and 21) since a control signal may be applied via the hollow core of the fiber. A voltage applied via electrodes 706 and 708 across the quantum well thin film alters the optical loss experienced by the WGM optical wave due to the quantum well thin film (by one of several mechanisms: the frequency of the absorbance peak of the quantum well material may be shifted into and out of resonance with the resonant WGM optical wave via an electro-absorption mechanism; carriers may be injected into a semiconductor or quantum well structure thereby changing the absorbance). Alternatively, the quantum well material may be provided without the electrodes, and the optical loss due to the quantum well material controlled by illumination of a semiconductor or quantum well material, thereby changing its absorbance characteristics.

Techniques for wafer bonding, cold welding, thin film application/depostion and the like may be found in the following publications: Xiao et al., Sensors and Actuators A - Physical **71** 123 (1998); Wada et al., Japanese Journal of Applied Physics Part 1 **37** 1383 (1998); Wada et al., IEEE Photonics Technology Letters **8** 173 (1996); Tan et al., Electronics Letters **31** 588 (1995); Wada et al., Japanese Journal of Applied Physics Part 1 **33** 4878 (1994); Yablonovitch et al., Applied Physics Letters **59** 3159 (1991); Wada et al., Proceedings of the 3rd International

Symposium on Semiconductor Wafer Bonding Science, Technology, and Applications, **95-97** 579, The Electrochemical Society (Pennington NJ, 1995). Each of these publications is incorporated by reference in its entirety as if fully set forth herein.

The application of a control signal to a modulator of a WGM resonator via a modulator control element enables controlled modulation of the optical power transmitted through the transmission optical fiber of the optical power control device. This may be accomplished in a variety of ways, depending on the nature of the modulator employed, and several specific examples follow. Modulating the optical loss of the WGM resonator between essentially zero loss and the so-called critical-coupling loss (wherein the WGM loss roughly equals the coupling between the transmission fiber and the WGM resonator) enables modulation of an optical wave that is resonant with a whispering-gallery mode of the WGM resonator between about 0% (substantially unattenuated transmission) and about 100% (substantially blocked transmission). A similar result may be obtained by keeping the WGM optical loss constant while modulating the optical coupling between the transmission optical fiber and the WGM resonator. Alternatively, modulating a resonant frequency of a WGM having optical loss substantially equal to the critical-coupling loss may enable similar modulation of an optical wave as the WGM resonant frequency is moved out of and brought into resonance with the optical wave. The foregoing are exemplary only, and many other transmission optical fiber modulation schemes may be devised by suitable modulation of WGM resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein.

In addition to the transmission optical fiber and the WGM resonator (including a modulator) and a modulator control element, an optical power control device according to the present invention may further comprise a secondary optical assembly positioned on the alignment device substantially tangentially engaged with the WGM resonator fiber segment. The secondary optical assembly may therefore be optically coupled to the WGM resonator, and coupled to the transmission optical fiber therethrough. The modulator may be employed to modulate the optical coupling between the secondary optical assembly and the transmission optical fiber through modulation of optical properties of the WGM resonator and/or coupling between the WGM resonator and the transmission optical fiber and/or the secondary optical assembly in a manner similar to that described hereinabove. The secondary optical assembly may comprise a second optical transmission fiber 750 (thereby enabling controlled switching of an optical wave

propagating along the first transmission optical fiber 600 to the second transmission optical fiber 750; Figure 22), or the secondary optical assembly may comprise a second WGM optical resonator 760 (thereby enabling, for example, controlled modification/modulation of the overall properties of the optical power control device, particularly the wavelength dependence of the control device; Figure 23). The secondary optical assembly may be positioned on and secured to the alignment device 500 on the same alignment substrate 502 as the first transmission optical fiber 600 and first WGM resonator 100, or the alignment device may comprise a second alignment substrate 770 with the secondary optical assembly positioned and secured thereto. Such a secondary optical assembly and/or second alignment substrate may be suitably indexed or provided with mating alignment structure(s) to enable reproducible, reliable, and stable alignment of the secondary optical assembly with the first WGM resonator when the optical power control device is assembled. The alignment device, including the first transmission optical fiber, the first WGM optical resonator, and the secondary optical assembly, may be sealed (preferably hermetically sealed) after assembly, as disclosed hereinabove. A cover, the second alignment substrate, or another functionally equivalent component may be positioned over the alignment grooves and sealed into place (using welding, fusion, adhesives, epoxies, resins, polymers, solders, and/or the like), leaving only the two ends of the transmission optical fiber exposed for connecting to an optical power transmission system. A portion of the modulator control element may reside on and/or within the assembled alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device. Such access may comprise feed-through connectors, access ports, embedded conductors and/or optical fibers, and the like for transmitting optical, electronic, or mechanical control signals.

Instead of providing the modulator on the WGM resonator, the modulator may alternatively comprise a separate modulator optical assembly. Modulation of the optical properties of the modulator optical assembly (rather than modulation of the optical properties of the WGM resonator) serves to modulate the optical power transmitted through the transmission optical fiber. As shown in Figure 24, the modulator optical assembly 902 may preferably be positioned in substantial tangential engagement with the WGM resonator fiber segment 100 (and therefore optically coupled to the WGM resonator) and secured to the alignment device. The modulator optical assembly 902 may comprise any of a wide variety of devices, including but not limited to: an optical gain and/or loss modulator, a non-linear optical device, an electro-optic

device, an electro-absorptive device, a semiconductor device (including semiconductor heterostructures, such as quantum wells), a second transmission optical fiber, a second WGM resonator (which may further comprise a modulator, as described above). The optical properties of the modulator optical assembly 902 may be controlled and/or modulated to modulate the transmission of optical power through the transmission optical fiber as described hereinabove for a modulator provided on the WGM resonator. A control signal (electronic, optical, mechanical, or other) may be applied to the modulator optical assembly as described hereinabove, and the alignment device may comprise a component (a modulator control element) for delivering such control signals to the modulator optical assembly, as described hereinabove. The application of a control signal to the modulator optical assembly 902 via a modulator control element enables controlled modulation of the optical power transmitted through the transmission optical fiber 600 of the optical power control device and may be accomplished in a variety of ways, depending on the nature of the modulator employed. Several specific examples follow. Modulating the optical loss of an optical loss modulator optically coupled to the WGM resonator between essentially zero loss and the so-called critical-coupling loss (wherein the loss roughly equals the coupling between the transmission fiber and the WGM resonator) enables modulation of an optical wave that is resonant with a whispering-gallery mode of the WGM resonator between about 0% (substantially unattenuated transmission) and about 100% (substantially blocked transmission). A similar result may be obtained by keeping the modulator optical loss constant while modulating the optical coupling between the modulator optical assembly and the WGM resonator. Alternatively, modulating a resonant frequency of a second WGM (part of the modulator optical assembly) having optical loss substantially equal to the critical-coupling loss may enable similar modulation of an optical wave as the second WGM resonant frequency is moved out of and brought into resonance with the optical wave. The foregoing are exemplary only, and many other transmission optical fiber modulation schemes may be devised by suitable modulation of WGM resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein.

The modulator optical assembly 902 may be positioned on and secured to the alignment device 500 on the same alignment substrate 502 as the transmission optical fiber 600 and WGM resonator 100, or the alignment device 500 may comprise a second alignment substrate 900 with the modulator optical assembly 902 positioned and secured thereto (Figure 24). The modulator

optical assembly and/or second alignment substrate may be suitably indexed or provided with mating alignment structure(s) to enable reproducible, reliable, and stable alignment of the modulator optical assembly with the WGM resonator when the optical power control device is assembled. The alignment device, including the transmission optical fiber, the WGM optical resonator, and the modulator optical assembly, may be sealed (preferably hermetically sealed) after assembly, as disclosed hereinabove. A cover, the second alignment substrate, or another functionally equivalent component may be positioned over the alignment grooves and sealed into place (using adhesives, epoxies, resins, polymers, solders, and/or the like), leaving only the two ends of the transmission optical fiber exposed for connecting to an optical power transmission system. A portion of the modulator control element may reside on and/or within the assembled alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device. Such access may comprise feed-through connectors, access ports, embedded conductors and/or optical fibers, and the like for transmitting optical, electronic, or mechanical control signals.

In the alternative embodiment illustrated in Figure 25, a plurality of WGM resonator fiber segments 100 are provided along a single optical fiber sufficiently close the each WGM resonator may be optically coupled longitudinally to its neighboring WGM resonators. Transmission optical fiber 600 may be optically coupled to a first resonator fiber segment 100, and a second transmission optical fiber 750 may be optically coupled to a second resonator fiber segment 100. Appropriate selection of a combination of resonant frequencies for each of the resonator fiber segments 100 enables tailoring of the frequency dependence of the overall optical coupling between optical fiber 600 and optical fiber 750 via the plurality of resonator fiber segments 100. In this way optical power control devices having specifically designed/tailored frequency characteristics may be fabricated.

The alignment device, comprising one or more grooved and/or indexed alignment substrates, may be fabricated from a material sufficiently rigid to provide reliable, reproducible, and stable positioning of the transmission optical fiber, WGM resonator, and any secondary or modulator optical assembly that comprise the optical power control device. Preferred materials may include ceramics or semiconductors such as silicon or a III-V semiconductor, but other material (such as metals, alloys, glasses, crystalline materials, and dielectric materials) may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein.

The fiber-alignment groove and the resonator-alignment groove may be formed by any suitable means for machining (or otherwise processing) the material used. A preferred method for providing the grooves is laser machining (most preferably ablative laser machining with an excimer laser), however, other fabrication techniques may be employed, such as lithographic patterning of a mask followed by wet (chemical) or dry (reactive ion) etching, electric discharge machining, plasma discharge machining, or single wire arc ablation. These same machining/processing techniques may be employed for providing other alignment and/or indexing structures on the alignment device (such as tabs, slots, pins, holes, grooves, and the like).

Laser machining has been set forth as a preferred method for spatially-selective removal of material from the optical fiber at various points in the fabrication process of the whispering-gallery-mode resonator (for patterning etch masks, deposition masks, diffusion and/or doping masks, and so forth). While remaining within the scope of inventive concepts disclosed and/or claimed herein, other methods for patterned removal of material from the optical fiber may be employed, including but not limited to: lithographic methods, optical patterning of photosensitive materials and/or photo-resists, mechanical techniques, electric or plasma discharge techniques, combinations thereof, and/or functional equivalents thereof.

The present invention has been set forth in the forms of its preferred and alternative embodiments. It is nevertheless intended that modifications to the disclosed resonant optical power control devices and methods of fabrication thereof may be made while remaining within the scope of inventive concepts disclosed and/or claimed herein.